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Mechanical Design of Radiation Shielding for NSLS-II

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Abstract **-** Radiation shielding of the NSLS-II facility is provided by bulk shielding, consisting of thick concrete tunnel walls and earth berms, as well as numerous supplemental shield assemblies. The supplemental shields were expanded to meet the enlarged scope of accidental beam loss scenarios. In this paper we discuss the process of providing the supplemental shields, starting from physics calculations through to final installation. This process included iterative interaction with the physicists and system engineers to overcome various design constraints, 3-D modeling and design, fabrication and procurement, field installation, and final safety approval. Some examples of challenging shielding configurations and their mechanical designs are presented.

Keywords**:** National Synchrotron Light Source II (NSLS-II), Storage Ring (SR), Local Shielding Design Coordination Group (LSDCG), Ratchet Wall Collimator (RCO)

1. Introduction

Efficient and timely installation of local shielding at NSLS-II did not happen immediately, but only after realization that a group structure was required to meet challenging timeline goals. Working closely with different disciplines (physicists, designers, technicians, and quality control and safety staff), understanding what each could provide and being flexible to varying limitations (resources, scheduling and procurement) enabled goal achievement. Effective communication between the disciplines was the key to solving the problem of specifying, designing and installing all shields efficiently and safely.

2. General Principals of Radiation Shield Application

For all radiation, energy in the field is absorbed by transferring the primary particle energy to matter and by generating additional lower energy particles, until the energy is absorbed as heat. High energy radiation can cause ionization of the atoms in absorbing materials, and if the material is human tissues it will cause damage to the complex biological molecules necessary for the function of life. Shielding materials attenuate the radiation field by absorbing the energy in inert material, sparing the accelerator staff and users from the risk of high level radiation exposure. For the circulating high energy electrons in a synchrotron, a physical process called Bremsstrahlung or “breaking radiation” emits high energy photons or gamma rays and secondary or scattered lower energy electrons. The electrons decelerate by high impact interactions with the atoms in the shield or with residual gas molecules in the vacuum chamber. The gamma rays produce neutrons that are more penetrating in matter, and have even greater detrimental radiation effects to human tissues per unit of absorbed energy. Attenuating the neutrons requires inert materials, such as polyethylene and concrete. These materials have higher hydrogen content than lead, so they attenuate the neutrons more effectively. Density is an important property for attenuation within a given length, which increases with higher atomic number. The attenuation length is considered for the selection of commonly used shield materials, such as lead, concrete, iron, earth, high density polyethylene and aluminum, to absorb the radiation field at locations, to a safe level, while meeting cost and physical limitations of installing those materials. Lead has the shortest attenuation length for gammas. Polyethylene has the shortest length for low energy neutrons, but it does little for gamma rays. Steel and lead are similar for high energy neutrons. The selection of material and thickness is best determined by the radiation codes that address these factors with geometrical constraints.

The transverse limit of the local shields is determined by the extent of the electron beam's possible steering errors and of the width of the shower that is parameterized by the Molière Radius, R_m. The latter defines the effective radiation shower width as it passes through the material. By providing shield materials that extend at least three R_m past the center axis of the beam, minimizing the gaps in the material and increasing the overlap of layers, the radiation within the shower is effectively attenuated to low levels before hitting the bulk shield wall.

2. 1. Physics - Acquiring Specifications of Shields for NSLS-II

Accelerator physicists, with knowledge of accelerator beam behavior for normal and abnormal operations and familiarity of the design of the NSLS-II accelerators (200 MeV Linac, 3 GeV Booster and SR), were necessary to realistically determine where the accelerator beam could be lost. Special emphasis was placed on the Linac, Booster and Injection into the SR, since abnormal operation of magnets could miss-steer beam to one location and greatly exceed the bulk shield's attenuation capabilities. Once beam is stored (circulating) in the SR, abnormal operations of magnets or the RF system would most likely result in distributed beam losses around the SR tunnel, reducing the radiation level at any one location. However, the variation of bulk shielding attenuation around the NSLS-II SR required a special beam Loss Control and Monitoring (LCM) system, including SR beam scrapers, with shields, that would measure and limit high current beam losses to the more heavily shielded injection region. Additional shielding was added to this area to protect this more likely and higher beam loss potential.

Radiation physicists analyzed the impact of these possible beam losses using a state-of-the-art radiation calculation code (FLUKA) with realistic geometrical models of the bulk shielding, accelerator magnet structures and local shields, to accurately predict radiation dose rates to the occupied areas. This allowed the local shield designs to be iterated in thickness and geometrical extent, to ensure that radiation levels hitting the bulk shield walls were sufficiently attenuated to meet the tight administrative and regulatory dose rates for the high occupancy experimental floor of NSLS-II. When the dose rates at occupied spaces prove to be sufficiently low enough, (by experience with long term radiation records) then future users of this facility may not be required to wear radiation badges to access the experimental floor, saving time, training and cost for operating NSLS-II.

2. 2. The Bulk Shield Defined

The building and berm attenuate the radiation through their bulk shield walls. The equation used to determine each of their wall thicknesses was [1]:

$$H = \sum\{(F_i \times J/R^2)\} * e^{-(t/\lambda i)} \qquad \text{Dose Rate in mrem/hr} \qquad (1)$$

The radiation source term, F_i, of particle components (i = gamma, low and high energy neutrons) is generated from an assumed beam power loss, J (in kWatts), hitting a thick target (i.e., 30 cm of copper or steel) along the beam axis. The dose rate is calculated, transverse to the beam axis at a distance, R, from the target, after passing through a thickness, t, of shielding material, with attenuation length, λ_i. The total dose rate is the sum of the terms. For NSLS-II, the SR concrete walls, typically 100 cm thick, were calculated to attenuate radiation to dose levels < 0.5 mrem/hr at the surface of the outer wall, for an assumed operational beam loss rate of 1.1 nC/min for 3 GeV beam in the SR magnets. The assumptions in Eq. (1) are such that the measured dose rate should be at least 4-10 times less for these assumed losses. Local shields contribute additional products to the exponential attenuation factor of the wall. However, if the beam doesn't hit sufficient matter before hitting the shield wall then these calculations may greatly underestimate the dose rates outside of the walls, in the forward beam direction.

2. 3. Requirements for Local Shields

Operational losses that are greater than the assumed J levels for the bulk shield are additionally attenuated with local shields installed near the loss point. An example of an Operational Loss (OL) shield is a Beam Dump (see fig. 7), where the maximum J is the total beam power transported to the dump.

Steering Error Loss (SEL) and Beam Scatter Loss (BSL) are abnormal losses, which also require attenuation with local shields. The equation to determine the maximum steering angle, Θ_M, for a dipole magnet is [2]:

$$\Theta_M(\text{rad}) = 2 \cdot \sin^{-1}\left[\frac{B_M(T)\cdot L_m \cdot 0.29979}{2\cdot P_m(^{GeV}/_{c})}\right] \qquad \text{Max Angle for a Dipole} \qquad (2)$$

Where B_M is the maximum magnetic field, P_m is the minimum beam momentum, and L_m is the magnetic length. The full steering angle range is considered, including the possibility of the magnetic field being reversed. At NSLS-II, we require the major dipoles to have the field polarity insured by a stringent QA process. For this case, the minimum angle is typically when the magnet field is off. If Θ_M exceeds critical value, dose levels outside the shield wall require additional evaluation.

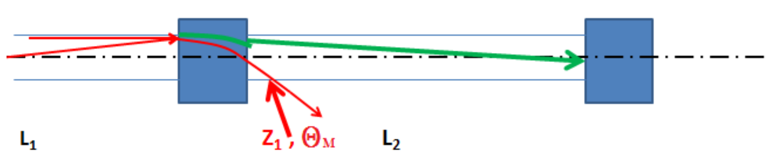

Fig. 1. Steering Angle, Θ_M, of electron beam by dipole magnet showing an SEL beam loss (red) and a safe steering error (green) which doesn't cause a beam loss.

SEL shields are defined where the entire beam current can be steered out of the beam pipe and not hit any significant amount of material before hitting the bulk shield wall. Examples of local shields for this purpose are the Booster Dipole Shadow Shields (see fig. 3 and 4) and the Septum Shields (see figs. 2 and 5), where the injection septum is off, causing the injected beam to hit the septum vacuum chamber wall. BSL shields are defined where a significant portion of the beam is scattered before it hits the bulk shield wall. Beam hits material inserted into its path and it diffuses, causing a shower to be initiated, but without enough thickness to be considered as a thick target. An example of a BSL is the SR Scraper Shield, where beam scrapers material, causing a shower when beam is intercepted.

Dose rates, for radiation propagating through SEL and BSL shields, were calculated using the Monte-Carlo radiation transport code FLUKA. Realistic models, including magnetic fields, local shields and bulk shields, were generated to estimate expected dose rates. If rates exceeded those permitted for the occupied space, local shield designs were expanded, to reduce levels, but limited by the constraints of geometry, time and cost. For the SR injection septum, models showed high values of dose on the experimental floor, so its length was extended and additional concrete was added, to reduce the neutron component of the dose to acceptable levels.

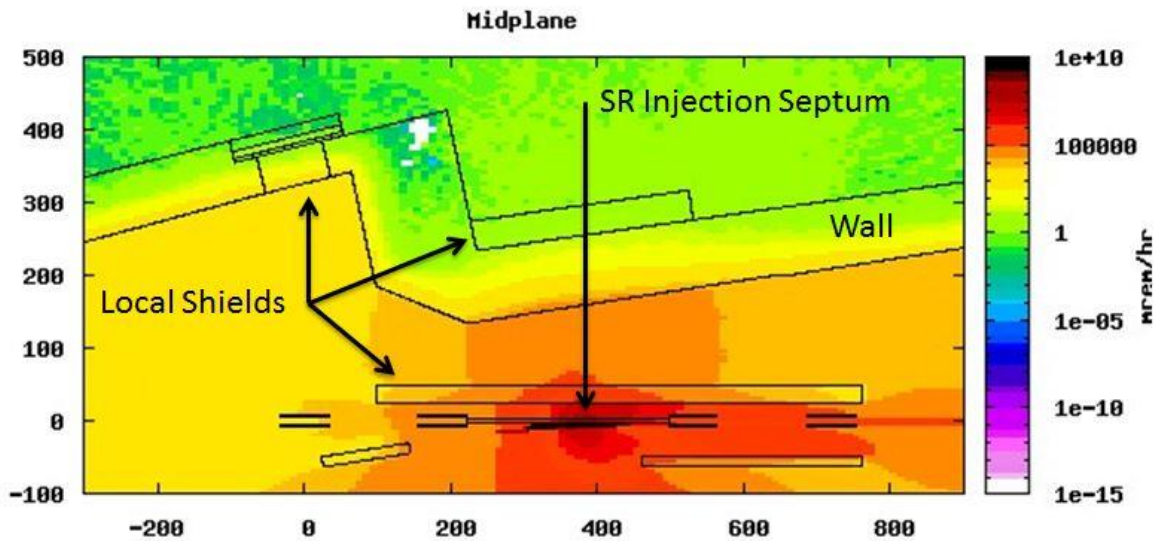

Fig. 2. FLUKA model of the SEL Injection Shields, with the injection beam hitting the septum with its field off. Local shields were expanded, to reduce dose rates outside the bulk shield, to acceptable levels.

3. Coordination – An Iterative Process

Coordinating information and sharing design intentions between many special disciplines was accomplished by establishing three meeting groups, Local Shield Design Coordination, Installation, and Shield Assembly and Quality Control. It enabled interactions for design concepts, through to the completed installation of certified local shields.

3. 1. Local Shielding Design Coordination Group

The LSDCG was established to adequately define need for local shields, including their location, size, materials, and design, based on physical analysis and mechanical limitations. Information regarding layout and operating parameters of the accelerators came from the physicists responsible for their beam transport designs. Engineers were able to recognize the needs and advise limitations, to enable adequate layouts of effective shields at an early stage of the project.

The benefits from the group included that FLUKA models were supported by accurate 3-D mechanical layouts and models. By reviewing layouts as a group, radiation risk areas outside the bulk shield were identified as radiological controlled spaces with administrative controls. Also, discussions resulted in locating shields that gave access to beam lines for maintenance. The reviews enabled targeting of major shield efforts, which helped establish resource dedication early. Preliminary approvals were given to shield models that were safely supported. The pre-approval process expedited formal review and release of drawings and enabled parallel purchasing and fabrication with unreleased drawings. The method used and the shields approved by the LSDCG were reviewed periodically by an Internal Radiation Committee for conformance. The body of the Requirements, Engineering Specifications and Interface Control document was written from the group's effort.

3. 2. Installation Coordination

Meetings were held weekly to discuss installation status and resource schedules for fabrication and installation. The venue gave opportunity to present and discuss preliminary designs and installation schedule with other systems groups. Tunnel walk through meetings were held to discuss conflicts, design adjustment options and safety.

3. 3. Shield Assembly and Quality Control

Meetings were established to confirm status and ensure goal that certified shields were installed in time for accelerator commissioning. All shields identified and defined by LSDCG were listed and progress was checked, including: mechanical drawings and formal release, raw material delivery, and part fabrication and shield installation. Travelers, instruction documents to verify the installation meets drawing specifications for quality control, also required approval and were on the check list. The list was handed over to Environmental, Safety and Health to aid configuration control of shields.

4. Machine Design and Drawing

The NSLS-II accelerators, transport lines and lattice were accurately modeled with 3D mechanical design software. Designing the local shields took full advantage of this resource, easily creating accurate layouts for review and using this utility to generate approved drawings.

4. 1. Trace Line Layouts and Review

With steering error specifications defined by LSDCG, preliminary shield models and layout views were generated for review. Designs were created by generating trace lines directly onto sketch planes of 3D lattice models. Screen shots were used for presentation to LSDCG and engineering groups. After obtaining preliminary approval from LSDCG, the models were detailed and 2D part and assembly drawings were generated. The mechanical designs were entered into the NSLS-II Mechanical Design Vault system and the drawings were approved by an Engineering Change Order review process for approval.

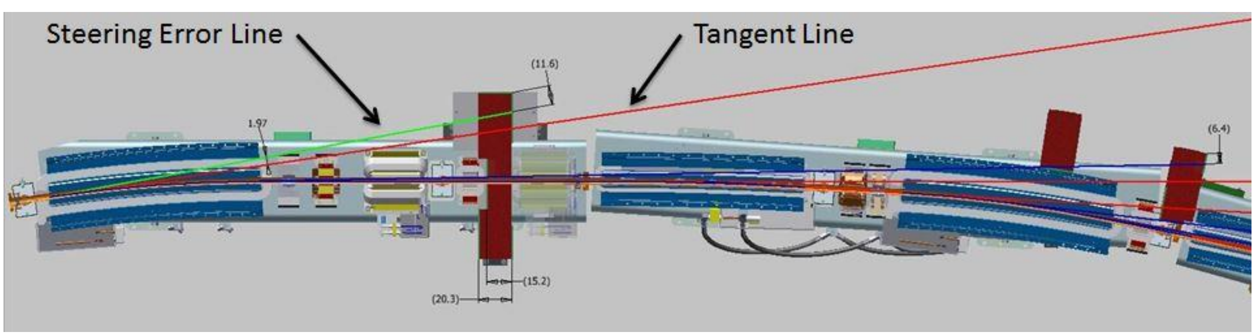

Fig. 3. Dipole steering angle trace lines were drawn on the assembly model sketch plane to locate shields.

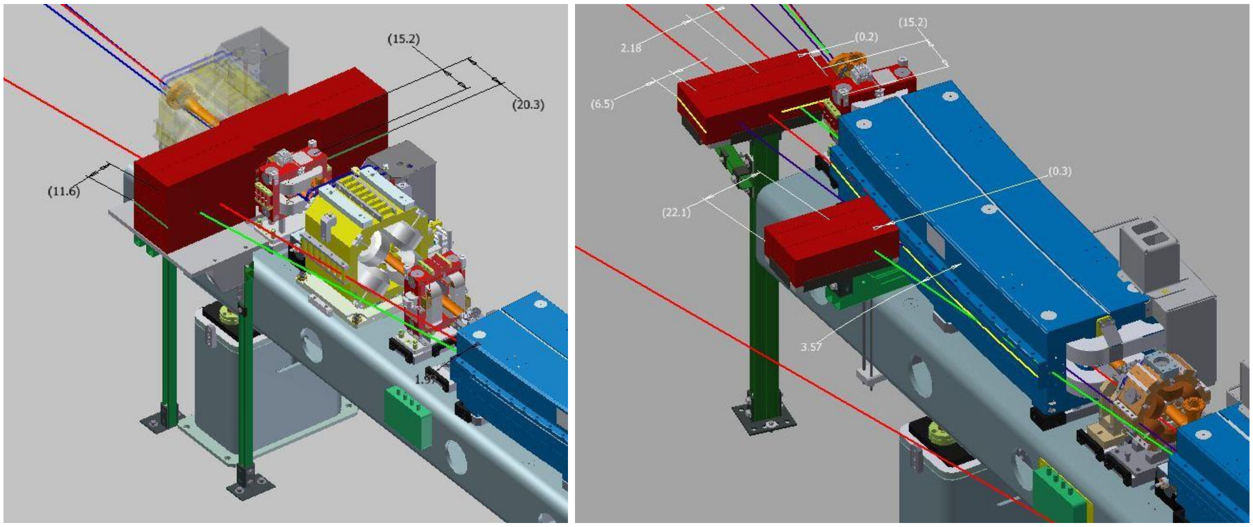

Fig. 4. Booster SEL Shields were reviewed by LSDCG, to verify location, size, construction and overlap.

4. 2. Machine Design

Most shield support frames were built from structural channels, where loads were verified against catalogued maximum load tables, for quick design. Some support frames were custom designed to carry and move heavy loads, to facilitate accelerator maintenance. The Injection Straight was shielded with such frames, and its design required careful planning and application of classic strength of material principles. The shield frames are pinned to I-Beam Trolleys, which are mounted on overhead Beams. Frames were loaded with lead, the heaviest at 7300 lb. Maximum bending and shear stress of pins were calculated, multiplied by a service factor and compared to material yield strength in shear. Test pins were loaded to design value with service factor, to guarantee safety. Lifting and pinning of frame was carefully handled by Brookhaven National Laboratory’s hoist and rigging group.

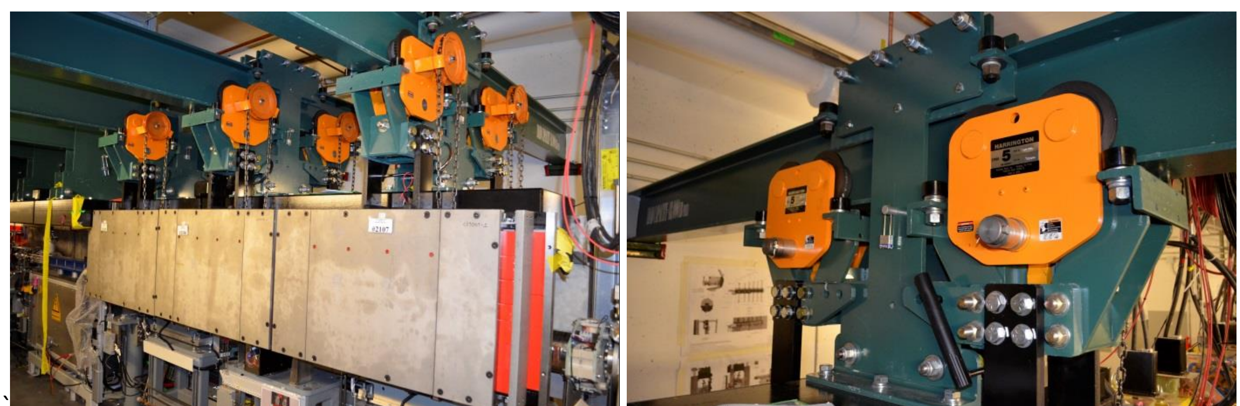

Fig. 5. Injection Straight Enclosure Shield frames required careful design and planning for safety.

5. Procurement and Fabrication

The commissioning timeline of the NSLS-II accelerators dictated the items selected for early procurement. The longest lead time item was molded lead bricks of standard size, which were painted to minimize lead residue. Procurement was planned in three stages. The Linac was to be commissioned first, so having all materials available, including support frame metals, for all of its shield installations was priority. The LSDCG review of shield layouts enabled early estimation of the long lead material requirements. Materials that remained from Linac would be used for Booster, and what remained from Booster was included in the final estimate of materials needed for the SR.

Fabrications of support frames were scheduled and parts were machined per layout drawings. For shield assemblies of multiple applications, frames were procured. An example of this is the 30 similar support frames required for SR dipole shadow shields.

6. Field Installation

All local shields were installed with approved assembly drawings and travelers. The shield material assembly drawings included multiple views of stacking and overlap requirements. A traveler was used to confirm the installation, so all requirements on the drawing are verified, including taking photos of multiple stacks, and measuring stack size and the installed distance from the beam line components.. The photos were reviewed and attached to the traveler, to confirm the shields are built to specifications.

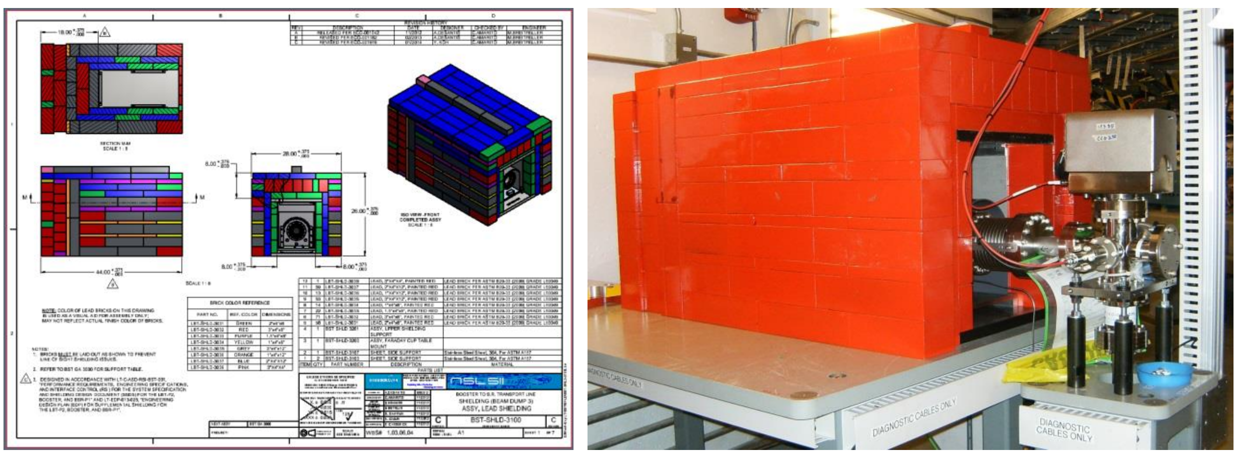

Fig. 6. Lead assembly drawing for Booster Beam Dump and finished assembly of lead bricks.

7. Final Safety Approval

The status list, that was generated to track installed certified shields, became useful for Environmental, Safety and Health. When the list reached maturation, it was handed over to ES&H and was transformed into a checklist to verify shield configuration and control for accelerator readiness. The travelers were forwarded to quality control and loaded onto a SharePoint site. QC reviews, certifies installation of the shield and notifies ES&H. With the checklist in hand, and QC confirmation that every shield on the list is certified, ES&H approves the shield system as safe. During commissioning of the accelerator, fault studies are executed to verify that the shields, as installed, are able prevent radiation levels from exceeding policy and remain as low as reasonably possible. If it is required to disassemble a shield, for any reason, a Safety Work Permit is issued for the work on that shield, and the shield is restored to its original specifications, per drawings and documented travelers. Formal reviews, approvals and redesigns are conducted by the Radiation Safety Committee.

8. Examples of Challenging Local Shield Configurations at NSLS-II

Many of the installation locations were not conducive for standard designs, so special planning and custom field engineering adjustments had to be made. Two examples are discussed.

8. 1.   Ratchet Wall Collimator (RCO)

The RCO is installed in the ratchet wall penetration and it shields the First Optics Enclosure from Insertion Device Bremsstrahlung and SR scatter radiation. A series of difficulties were overcome for proper installation. The precise assembly of collimator bricks at the wall penetration was deemed impossible, so a rigid chassis was designed to mount the vacuum chamber assembly, which includes a failsafe burn thru device, and collimator lead bricks. The chassis enabled precise position of all components in the shop and included lifting lugs for transport of the 550 lb. RCO to the wall penetration. Assembly in the shop also allows for testing and measuring, to specifications. The vacuum tube assembly straightness was not in spec. and bake-out thermal conditions can cause distortion, so the tube assembly was shimmed, heated and leak tested on the chassis to conform to final requirements of +/- 200 micron aperture position. Visibility of the Burn Thru Flange fiducials at wall penetration installation is not possible, so reference survey fiducials were added to chassis and a survey file was created. Now, at installation, visibility of chassis fiducials reveals critical location of the Burn Thru aperture.

Fig. 7. RCO Assembly completed and prepared for transport to penetration

During the construction of the building, the wall penetration sleeves were not installed within positional specifications, adding to the challenge. There was an unexpected and extreme variation of the location of penetrations in elevation and transverse, so a partial, lightweight RCO assembly is pre-surveyed in the penetration, to allow selection of proper shielding material thicknesses and minimize shield gaps for the full penetration length of 1.5 meter. The wall penetration sleeve is bowed and skewed, so custom machining of upstream shielding materials with shims and careful handling of the 68 lb. ratchet lead bricks is required, to not affect the final installed position of the RCO. For transfer of the RCO into the penetration, a stainless steel sheet is mounted in the penetration, to ease sliding, and a special lifting table is deployed to match elevations, so rough handling of the assembly is minimized while installing.

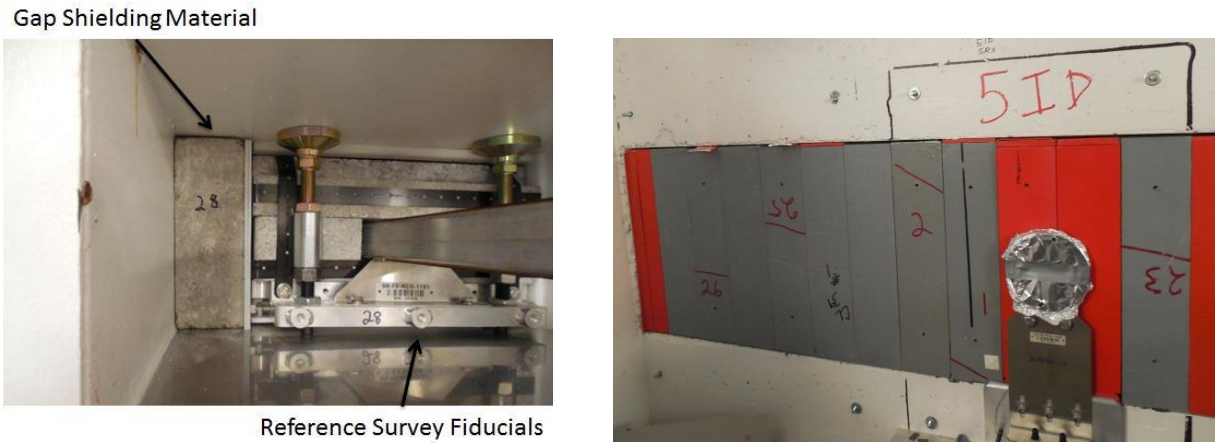

Fig. 8. RCO installed in penetration and ratchet lead re-installation

8. 2. Injection Straight Enclosure Shield

The SR Injection Straight is heavily shielded, as its septum functions to accept and steer 3GeV beam from the Booster to the Storage Ring. It can receive many off target firings and can be the source point of deadly levels of radiation. The shields must be movable, to enable routine maintenance of the straight's magnets. Some unique problems were solved for the installation of these shields.

The Upstream shield length requirement was increased 5' from its original early estimate, to encompass scatter from the upstream kicker magnet and booster transport line. The five pre-installed I-Beams were not located to support the entire shield structure length. An additional W10x30 I-Beam and columns were installed and load tested to carry 9 tons of rolling loads.

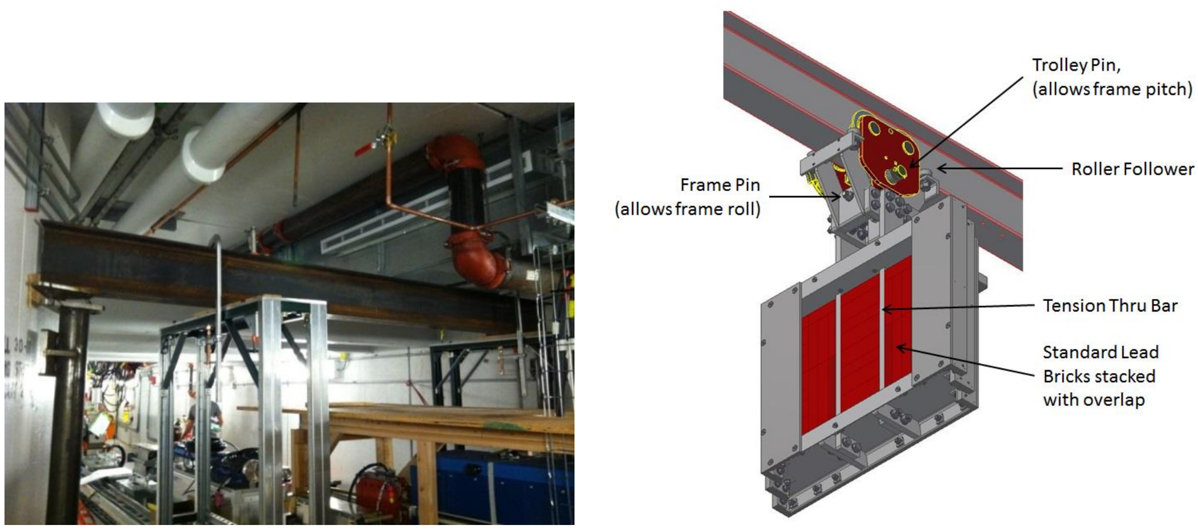

Fig. 9. Upstream I-Beam installation allows travel of Side Shield Compartment Frame

The challenging commissioning schedule required simultaneous installation of the Injection Straight SR magnets and shields. Also, large ventilation ducts were installed close to the I-Beams, giving limited space. Simple and effective approaches of design and installation were planned.

It was decided to utilize both top and bottom of the I-Beam to maximize space for bearing supports and gain maximum travel. The duct gave limited space for retraction travel of the Overhead Shield, so low profile, high load capacity roller bearings were selected to roll on top of the I-Beams. A hanging frame was assembled to these bearings and the frames allowed for pin fastening of the 8” thick, 4 ton steel slabs at an elevation that is just ½” above the septum. The Overhead Shield hanging frames were able to travel under the duct to an open floor area, and enabled safe lifting of heavy loads. The lead loaded Side Shields utilized a compartment frame design, to accept standard lead bricks. The frames were designed to allow pitch and roll, while traveling on the trolley, but used roller followers to control clearance. The Side Shields also included a pin mounting design, to allow safe lifting from an open area.

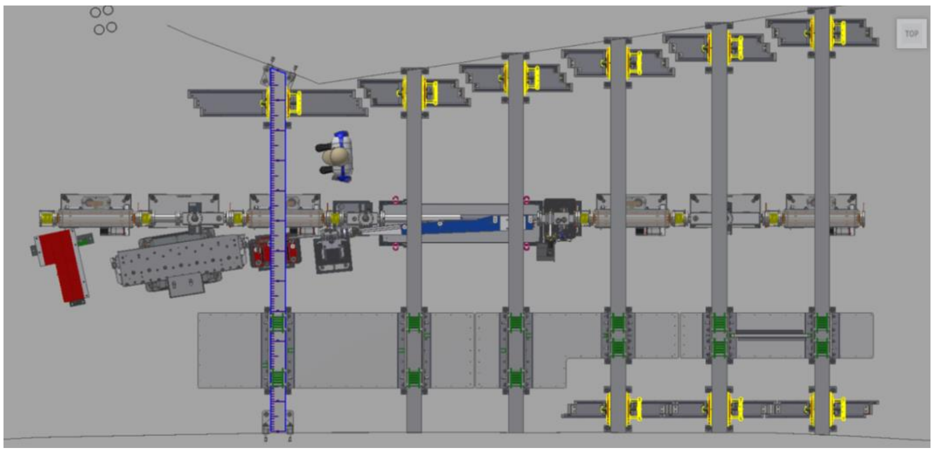

Fig. 10. Injection Straight Shields retract for service, and frames travel to open floor area for a safe lift.

9. Conclusion

NSLS-II is safely shielded by numerous supplemental shield assemblies. To minimize cost and maximize safety of the system, an iterative and interactive method was deployed to review requirements and approve shield designs. The establishment of the meeting groups and the informational exchange between them allowed for timely solutions of numerous challenges. Knowing what would be acceptable to commission the storage ring, early on, allowed for focus and solution of the major issues, while limiting problems to minor details that were manageable.

Acknowledgements

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References

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